Designing an adaptable and low-cost system for gesture recognition using visible light

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Preface

This work is created as part of the CSE3000 Research Project at the Delft University of Technology. This paper is part of a larger project: Gesture recognition empowered by Ambient light and Embedded AI. Which was contributed to by, in total, 5 students. Trough our combined research 5 individual papers have been created, with the recommended reading order as follows:

1. "Designing an adaptable and low-cost system for gesture recognition using visible light." (This paper)
2. "Designing a software receiver for gesture recognition with ambient light." by Dimitar Barantiev [6]
3. "Constructing a dataset for gesture recognition using ambient light." by Femi Akadiri [3]
4. "Recognising gestures using ambient light and convolutional neural networks." by William Narchi [14]
5. "Gesture recognition on arduino using recurrent neural networks and ambient light." by Matthew Lipski [11]

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Abstract

This paper describes the design of an adaptable, low-cost, and energy efficient gesture detection system. The system leverages the ambient light available in the environment to perform Visible Light Sensing (VLS) using powerful Convolutional Neural Networks. The focus lies on designing a system that is capable of robust gesture detection in any environment while only utilizing a limited number (3) of photodiode sensors. The research conducted in this paper contributes to two crucial aspects of VLS gesture recognition systems. First, it shows how the photodiode sensors can be automatically fine-tuned using four resistors to achieve excellent sensing performance in a wide range of lighting environments from 50 Lux up to 150k Lux. Secondly it is shown that a photodiode arrangement consisting of an equilateral triangle with sides of $5cm$ facilitates the highest performance and robustness using Dynamic Time Warping for general and user-friendly gestures.

1 Introduction

Existing applications which recognize gestures are systems such as eye-tracking using infrared light [17], gesture detection using WiFi [2], and gesture detection using the Microsoft Kinect [16, 9]. One aspect that all of these systems share, is a sensing medium, for example infrared light, which is controlled by the system itself. This is a crucial aspect where the research presented in this paper differs from most existing work, as it will focus on Visible Light Sensing (VLS) with uncontrolled ambient light.

Sensing with uncontrolled ambient light comes with some key advantages; the system has lower costs, better energy efficiency, and requires less space. However sensing with uncontrolled ambient light also comes with disadvantages; it is unclear how data should be interpreted, and it is also harder to be robust against changes in the environment.

A key area in the field of visible light sensing is that of sensing with ambient light while only utilizing a limited number of sensors. This research opportunity is formally described in research direction 6 of the paper by Wang et al. [19] and states: “Deploy receivers densely and smartly”. This research direction is interesting, as successful research will ultimately enable low-cost and energy-efficient VLS applications that can be deployed with tiny microcontrollers in any environment. In order to conduct this research, a system will be built consisting of one Arduino nano 33 BLE [5] and 3 OPT101 photodiodes [7].

1.1 Limitations of existing work

Existing research into visible light sensing with ambient lighting has resulted in systems that achieve high accuracy, but are limited in capabilities. These limitations can primarily be catagorized in two classes. The system is either not capable of recognizing complex gestures, as in SolarGest [12] which is only able to recognize 6 basic gestures using a single sensor, or the system uses an excessive amount of sensors (> 5) , as is the case for LightDigit [1] using 9 sensors, and for [10] using 16 sensors. These limitations indicate that there is a trade-off between the amount of sensors used and the complexity of gesture that is able to be recognized.

In addition to the limitations above most systems have only been shown to work while in predictable laboratory conditions, and it is unclear how the performance is affected by a different environment. The only exception to this is [10], which reported excellent robustness to environmental changes, however this system also utilized the most photodiodes.

1.2 Research Questions

As is evident from the limitations of existing work, there is a trade-off between the number of photodiodes and the performance/complexity of the gesture recognition system. The system developed in this paper only uses a limited number of 3 photodiodes. Therefore the research question is: *How to optimize the sensing performance of the (3) OPT101 photodiodes?* This research question can be split up in two more concrete sub-questions: (i) What is the impact of ambient light on the sensing performance? And (ii) what is the impact of the placement of photodiodes on the sensing performance? Below the relevance and challenges for each sub-question are explored.

(i) What is the impact of ambient light on the sensing performance?

The voltage output of the OPT101 is dependent on the level of lighting that hits the surface of the photodiode. Since the ambient lighting in the environment is not controlled by the system, it is important to understand the impact that the level of ambient lighting has on the output. Furthermore section 8.3.2 of the OPT101 datasheet [7] details how the responsivity, and thus the voltage output, of the photodiode can be adjusted through the use of a feedback circuit. By understanding the relation between the voltage output, the light level, and the feedback circuitry, it will be possible to develop a system that is capable of operating in different environments. After this, it will even be possible to use a digital potentiometer and develop a system that is able to adapt to a changing environment.

Another characteristic of the OPT101 is that, according to figure 1 of the datasheet [7], the responsivity peaks when infrared lighting hits the surface of the photodiode. In this paper it will be researched how different types of lighting, such as sunlight and artificial light impact the performance of the OPT101 photodiode.

(ii) What is the impact of the placement of photodiodes on the sensing performance?

The placement of the OPT101 photodiodes will determine the data that is received, therefore optimal placement will allow for maximizing the data gathered from the environment. If the system has access to more data, then machine learning models will be able to analyze this data better. This leads not only to more reliable detection of gestures, but also allows for the detection of an entirely new set of more complex gestures.

The placement of the 3 available photodiodes will form a triangle. The exact configuration of this triangle will depend on the following parameters:

- **Distance between photodiodes.** The distance is a crucial factor. For example a distance that is too small might not capture a gesture as there will only be a small time difference between signals, while a distance that is too large might not even capture the gesture completely.
- **Angle between photodiodes.** The angle between photodiodes can be used to further enhance the performance of the system. It can also be used to boost the detection of a specific gesture. A great example for this would be angles of (0, 180, 0), which results in a line and is excellent for detecting left-right hand gestures.

1.3 Contributions

This paper shows how a gesture detection system can be optimized mostly from a hardware perspective. Two crucial optimizations

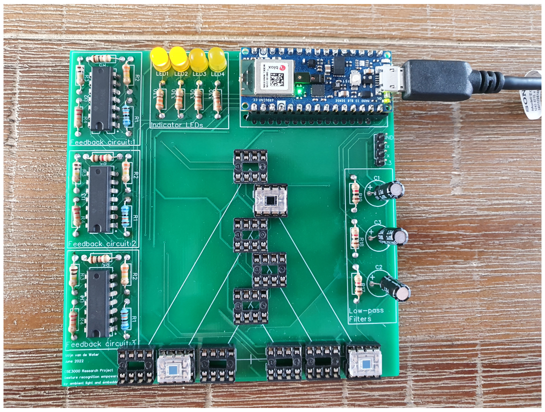


Figure 1: The Printed Circuit Board (PCB) developed for the research presented in this paper

are shown. Firstly it is shown which resistor values work best in certain environments, and it is shown that the optimal placement for detecting hand gestures is an equilateral triangle with sides of $5cm$. On top of these optimizations, this paper also discusses how such a system can adapt to a changing environment using software, ultimately enabling the gesture detection system to function in a range from 50 to 150k Lux. The final system is depicted in Figure 1.

1.4 Structure

First, section 2 will outline important techniques and clarify terms used in this paper. After that, section 3 provides an overview of the hardware, software, and other tools which were used to conduct this research. In section 4, the theoretical design and research methods are described, with section 5 detailing the implementation. The results are then discussed in section 6, and compared to related work in section 7. Finally the paper is concluded and future work is outlined in section 9.

In addition to the main content of this paper, section 8 specifies what has been done to ensure that the research has been conducted in a responsible manner as well as how the results can be reproduced. There is also an appendix present after the paper, which includes all images shown in the paper along with additional images not present in the paper. The appendix also contains additional information which is not directly relevant to the paper.

2 Background

This section briefly explains the main concepts and technologies that are used in this paper. Additionally this section aims to clear any ambiguity of terms, such as ambient light and photodiode, that are used frequently throughout the paper.

2.1 Visible light sensing

Visible light sensing (VLS) works on the principle that incoming light rays from the environment will be blocked when an object, such as a hand, comes close to the sensor. A simple sensor such as a photodiode senses this change in incoming light and adjusts its output accordingly. This way the photodiode functions as a distance sensor. The signals of single or multiple of these sensors can then be processed, using for example machine learning, in order to detect movements and gestures.

Another way VLS can be implemented is by modulating an LED and encoding a message. For example the LED can be turned on to send a 1, or turned off to send a 0. A receiver can then decode this message and process it.

2.2 Ambient light

Uncontrolled ambient light refers to light sources that are outside the systems control. Examples that are considered as uncontrolled ambient light sources are sunlight, street lights, ceiling lights, and other types of lighting that are present naturally in an environment.

2.3 Photodiode

A photodiode is a device that, much like a traditional solar panel, captures light and converts this into an electrical current. In the case of the OPT101 used in this paper, the electrical current is amplified by an internal operational amplifier; resulting in a voltage output. The functionality of the op amp can easily be exploited by connecting feedback circuitry, consisting of resistors and capacitors, between the output and inverted input of the op amp. The final output voltage of the OPT101 photodiode follows the following formula:

$$V_{out} = I_D * R_F + V_B \tag{1}$$

Where I_D is the photocurrent, R_F is the resistive value of the feedback circuitry, and V_B is a constant voltage of approximately 7.5 mV.

From Equation 1, it becomes clear that the output voltage is largely dependant on both the photocurrent I_D and the resistive value R_F. This means that uncontrolled changes in ambient lighting, and thus I_D, can be compesated by adjusting R_F accordingly. This allows for normalization of the output voltage in a large range of ambient lighting conditions using only hardware.

2.4 Dynamic time warping

Dynamic time warping (DTW) is a technique that is often used to analyze the similarity between two temporal sequences [13]. The algorithm that performs DTW is a dynamic programming algorithm that aims to find the optimal alignment between two time series data, which can vary in both starting time and speed. To achieve this, the algorithm is allowed to warp time in a non-linear manner, meaning that the data of one sequence is stretched and compressed in order to optimally match it to the other. Main applications of DTW are speech [4], and gesture [12] recognition. In this paper DTW will be used in order to optimally align two gestures, after which the leftover distance between the two optimally aligned gestures can be calculated by a simple euclidean distance metric.

3 System overview

3.1 Hardware

The hardware for the gesture recognition system consists of 3 OPT101 photodiodes, 1 Arduino Nano 33 BLE microcontroller, 3 CD4016BE switches, and a range of passive components (resistors and capacitors). Figure 2 contains the wiring diagram for a single OPT101 photodiode. Additional photodiodes can be added, by duplicating the current setup and selecting a new analog pin from the Arduino.

The Arduino board is responsible for reading the OPT101 sensor output at a constant frequency, pre-processsing this data, and finally performing inference using TensorFlow Lite for Microcontrollers. In addition to the OPT101 and Arduino board, there are some extra components that improve the effectiveness of the system. First of all an RC low-pass filter is added which, as the name suggests, only allows low frequency signals to pass through and filters out any high frequency noise. Another crucial component is the feedback circuitry for the OPT101 photodiode, which essentially functions as a single resistor, however the value of this resistor can be dynamically changed as required by setting different combinations of the available resistors in series using the

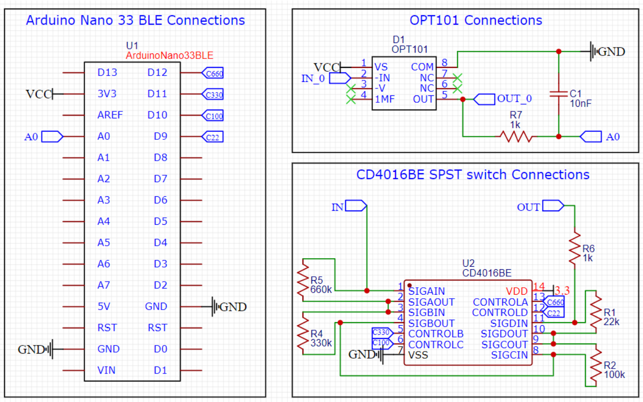


Figure 2: Wiring diagram with a single OPT101 photodiode. Each additional OPT101 photodiode requires an additional CD4016BE setup and an analog pin from the Arduino.

CD4016BE switches. Table 1 provides an overview of all used components. The system is optimized for cost, energy, and space efficiency. The system costs only €31.22, draws $15mA$ of current[1], and fits on a 10cm x 10cm PCB. This PCB is shown in Figure 1.

List of components

Component	Unit price	Quantity	Price
Arduino Nano 33 BLE	€19.30	1	€19.30
OPT101	€3.17	3	€9.51
CD4016BE	€0.61	3	€1.83
Custom PCB	€0.58	1	€0.58
660 kΩ resistor	-	3	-
330 kΩ resistor	-	3	-
100 kΩ resistor	-	3	-
22 kΩ resistor	-	3	-
1 kΩ resistor	-	6	-
10 nF capcitor	-	3	-

Table 1: List of components along with quantities and prices. The price of passive components have been neglected and all prices exclude shipping costs.

3.2 Tools

During this research various tools have been used. The most prominent tool that has been used is a light level meter, which measures the light level in Lux present in the environment. Another device that has been used frequently is an electrical multimeter, which was used to measure various characteristics of the circuit such as voltage, current, and resistance.

There are also many software tools which have been used extensively. The PlatformIO plugin for VSCode was used to program the board and the Arduino IDE serial plotter has been used to quickly display the sensor readings.

4 Design and Methodology

This section outlines the theoretical foundation and ideas behind the solutions to the research questions. Furthermore this section will describe in detail the methods of how each research question was approached.

[1]Peak current, running the code required for the work presented in this paper. The lit LEDs are included in this power measurement.

4.1 Impact of ambient light

When using visible light as a sensing medium the system is susceptible to the ambient light from the environment. The amount of ambient light that hits the photodiode directly determines the voltage output. Both the impact of the ambient light level and type are discussed.

Impact of ambient light level

The level of ambient lighting has a big influence on the final voltage output. Equation 1 shows that the voltage output is linearly dependant on the photocurrent I_D. The impact of changes in ambient light can be greatly reduced by using data-normalization techniques. Previous work has shown great accuracy when using normalization techniques such as the z-score transform, discrete wavelet transform, and dynamic time warping [12]. However, sometimes no amount of data-normalization can help to properly sense a gesture. This occurs in two cases, which are demonstrated in figure 3:

- The ambient light level is too high (green line), meaning that a gesture will not block enough light and the sensor reading stays maximum for much of the gesture.
- The ambient light level is too low (blue line), meaning that a gesture will not make much difference to the sensor reading as the reading was already close to minimum.

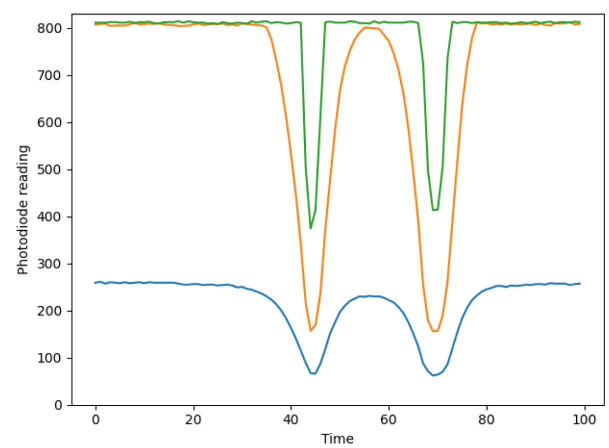


Figure 3: Figure showing how the effective sensing range of a photodiode can be adjusted using resistors. Gesture: 2x moving hand up and down (Double Tap).
The green sensor reading is only able to detect the hand when it is down, at other points the reading is maximum. The orange sensor reading is able to fully capture both when the hand is up and when the hand is down. The blue sensor reading is also able to detect the full gesture, however the difference between up and down is more subtle. Overall the *Orange sensor performs best*.
Green: 1MΩ, Orange: 330kΩ, Blue: 100kΩ

In both cases the level of ambient lighting is ’out of range’ and gestures are unable to be performed in an user friendly manner or gestures are not even able to be recognized at all. Luckily it is possible to change the effective range of the OPT101 photodiode. Equation 1 shows that the voltage output is also linearly dependant on R_F, the resistive value of the feedback circuitry. This is the only parameter of that is controllable by the system.

By selecting the correct resistive value R_F for the feedback circuitry, it is possible to exploit Equation 1 in order to adjust V_{out} and ensure that the system is operating in its effective range regardless of the ambient light level present in the environment.

This is what is actually shown in Figure 3, where the red line (330 kΩ) is best adjusted to the current environment.

It is even possible to take this a step further, by employing a digital potentiometer. The system can automatically adjust its effective range to adapt to a changing environment in real time. Since all additional components are hardware only, this means that there is very little computational overhead required for the system to automatically adapt to the environment.

Impact of ambient light type

The datasheet of the OPT101 shows that the spectral responsivity varies with the wavelength of light [7]. A higher spectral responsivity means that the generated photocurrent I_D is higher, which, as stated in the previous section, can again be compensated for by appropriately adjusting R_F. Therefore the exact wavelength has no effect on the sensing performance. However it is important to note that in extreme cases, like infrared and UV, the system may not have access to the required resistor R_F and might therefore still struggle sensing gestures.

Certain artificial ambient lights that are powered by 50Hz AC current also emit light with 50Hz noise. This noise may cause the sensor readings to be off, making gesture detection harder. In order to perform accurate gesture detection it is important to reduce or even entirely remove this 50Hz noise. According to the Nyquist–Shannon sampling theorem [15], if the measured signal contains no frequencies higher than B Hz then it is possible to completely reconstruct this signal by measuring at a frequency of at least $2B$ Hz. The situation mentioned above has as the highest relevant frequency the 50Hz noise. By applying this theorem it can be concluded that the full signal can be reconstructed when measuring at a frequency of at least 100Hz. By subsequently averaging multiple samples together it is possible to greatly reduce the effect of the noise present in the ambient lighting.

Methodology

In order to research the impact of ambient light and allow the system to operate in the correct range at all times, Equation 1 will be studied in detail. The system will be deployed in various different environments. For each environment the level of light intensity in Lux will be noted along with the value of the resistor in Ohm (Ω), that allows the photodiode to operate in the correct range. The goal is to create a reference table, which can assist in choosing the correct resistor for a given light intensity.

4.2 Impact of photodiode placement

The combined placement of the 3 available photodiodes is of large influence on the final performance of the gesture detection system. The theoretical impact of distance, angle, and individual rotation on the sensing performance is discussed. It is also mentioned which values for each parameter are considered and researched.

Distance between photodiodes

The distance between photodiodes is the most crucial parameter when it comes to placement. This is because the distance between the photodiodes determines the area that is covered by the photodiode triangle.

Valid arguments can be formulated for both increasing and limiting the distance between photodiodes. Increasing the distance means that the area of the triangle is larger, resulting in more variety and distinctiveness in the data, as the hand takes slightly more time to travel across the photodiodes. Limiting the distance however aims to solve practical issues. For instance if the distance between photodiodes is too large, say 1.5x the width of a hand, then gestures such as "tap" or "double tap" will not cover all required photodiodes, this can result in incorrectly detected gestures. In addition to this a limited distance will also help in reducing local environmental noise. If for example a small shadow is present on one of the photodiodes, then a single photodiode will contain incorrect readings. Reducing the distance such that all photodiodes are covered by the shadow means that the entire system can reconfigure itself, resulting in correctly functioning photodiodes. Finally a smaller distance between photodiodes can be packaged more tightly on a PCB or inside a system, which can save on the costs of a system. For this system distances from 2cm to 6cm (slightly less than the average hand width of 7.9 cm [18]) are considered.

Angle between photodiodes

The angle between photodiodes is able to increase the performance for a specific set of gestures. Consider for example angles of (0, 180, 0), which forms a straight line and is excellent for sensing left-right gestures. Another example of this would be angles of (45, 90, 45), which would enable sensing right-up or down-right gestures.

This system should be capable of sensing gestures along all directions. For this the system requires angles that allow to sense along all axis. The most logical are angles of (60, 60, 60). This will be used as a starting point and will be compared against other sets of angles.

Methodology

It is crucial to define the set of gestures for which the photodiode placement has to be optimized. A team member found that three photodiodes should be capable of recognizing the following user-friendly gestures [3]: Swipe Left, Swipe Right, Swipe Up, Swipe Down, Clockwise, CounterClockwise, Tap, and finally Double Tap. Most of these gestures are essentially a movement in one of six different directions, with others being repeats, or slight variations.

To most photodiode placements the Clockwise and CounterClockwise gestures are essentially captured the same as a gesture Swipe Left or Swipe Right executed twice. These gestures along with the Double Tap gesture, will not be used to score the photodiode configurations. Repeating gestures namely interfere slightly with the way data normalization works, which leads to inconsistent behaviour in the algorithm used for analysis.

In order to analyze the impact of parameters such as distance and angle, the experiments must be repeated with small variation in photodiode configuration. The 9 configurations in Table 2 will be considered, where each triangle differs in either width, height or both.

Data corresponding to each configuration will be gathered from 4 different ambient light environments: 250, 500, 1500, and 10000 Lux. During each data collection session 10 samples of the previously mentioned gestures are collected, 5 from the right hand, and 5 from the left hand. This gives 9 (configurations) $*$ 4 (light intensities) $*$ 10 (samples) $*$ 5 (gestures) = 1800 gestures that will be used to calculate a final scores.

5 Implementation

5.1 Impact of ambient light

The impact of ambient light will be researched in the following manner. First the Arduino and a single OPT101 is set up on a breadboard. Then between pin 2 and pin 5 of the OPT101 a feedback resistance R_f is placed. Since the implementation is on a breadboard R_f can be replaced quickly and easily. With this setup the OPT101 is subjected to many different light intensities. For each light intensity, R_f is often replaced in order to find the optimal resistor. The optimal resistor is defined as the highest value

Configuration parameters

Distances			Angles		
a	b	c	θ	ϕ	ω
2	2	2	60	60	60
4	2	4	75	30	75
6	2	6	80	20	80
3	3	3	60	60	60
3	4	3	60	60	60
4	4	4	60	60	60
4	6	4	25	130	25
5	5	5	60	60	60
6	6	6	60	60	60

Table 2: Configuration parameters for each photodiode arrangement. All configurations are possible on the PCB shown in Figure 1.
Distance A is the distance between the bottom left and the top photodiodes, distance B is the distance between the bottom left and the bottom right photodiodes, and distance C is the distance between the top and the bottom right photodiode.
θ is the angle at the bottom left photodiode, ϕ is the angle at the top photodiode, and ω is the angle at the bottom right photodiode.
Each photodiode configuration will be abbreviated as ABC_$\theta\phi\omega$ (Example 222_606060)

resistor with a default sensor reading (no shadow from the hand) below 800.

Digital potentiometer

In subsection 4.1 it is described how Equation 1 can be exploited in order to adjust the effective sensing range of the photodiodes. Automatic adjustment of the effective sensing range requires the system to have access to different values of resistors, which need to be selected electrically during runtime. To facilitate this a digital potentiometer can be used. However, commercially available digital potentiometers do not contain the required range of resistive values. As alternative a custom digital potentiometer was designed using SPST (Single Pole Single Throw) switches and resistors. This digital potentiometer will replace R_f mentioned above, and will thus be connected between pin 2 and 5 of the OPT101 photodiode.

The switch IC that has been used is the CD4016BE, which consists of 4 individual SPST switches. Each switch contains an input, output, and control. A resistor is connected between the input and output of the switch.

Electrical current arrives at the input of the switch. Since a resistor R_f is placed between the input and output of the switch electrical current can always flow, however it does so through a resistor and therefore experiences resistance. The switch also has a resistance, noted as R_{on} and R_{off}, for the on and off states. This circuit can effectively be modeled as two resistors in parallel, where the second resistor can change between two values based on a control signal. By examining the equation of how parallel resistances add in inverse, as shown in equation 2, it becomes clear that it is possible to control the effective input-output resistance by changing the state of the switch.

$$\frac{1}{R_{tot}} = \frac{1}{R_1} + \frac{1}{R_2} \tag{2}$$

To give a concrete example let R_f = $330k\Omega$. According to the datasheet of the CD4016BE switch, R_{on} and R_{off} are 280Ω [2] and $180G\Omega$ [3] respectively [8]. The switch can be in two states and the effective resistance can be calculated using Equation 2:

- ON state. $R_1 = 330\ k\Omega, R_2 = 280\ \Omega$. This results in $R_{tot} = 279.8\ \Omega$
- OFF state. $R_1 = 330\ k\Omega, R_2 = 180\ G\Omega$. This results in $R_{tot} = 330.0\ k\Omega$

This example shows that the resistor R_f can either be bypassed by turning on the switch. Or, when the switch is off it is possible to obtain a resistance that is equal to the original resistor. In this way the effective input-ouptut resistance of the switch is either negligible or equal to the chosen resistor. When combining mulitple SPST switches in series it is possible to add their input-output resistances together according to equation 3.

$$R_{tot} = R_1 + \cdots + R_n \tag{3}$$

The most important point is that each individual input-output resistance of a single switch can be set independently by a applying a voltage signal, using for example a microcontroller . When using N switches in series, the system has access to 2^N different combinations of resistors. In the system described in section 3, a maximum of 4 switches have been put in series, allowing the system access to up to 16 different combinations. The values of the resistors are shown in Table 1, and are further elaborated on in section 6.

Digital potentiometer software implementation

The software developed to allow for automatic configuration of the photodiodes consists of a class *LightIntensityRegulator*. When an object of this class is constructed the system will configure itself automatically. This is done using two important functions: *resistorDown* and *resistorUp*, which activate either the resistor before or after the currently selected resistor, and return true on success and false upon failure. The system aims to configure the photodiodes in a way such that the photodiode reading falls between a *Minimum_threshold* and a *Maximum_threshold*. The code is flexible enough to support any number of SPST switches as long as enough microcontroller pins are available.

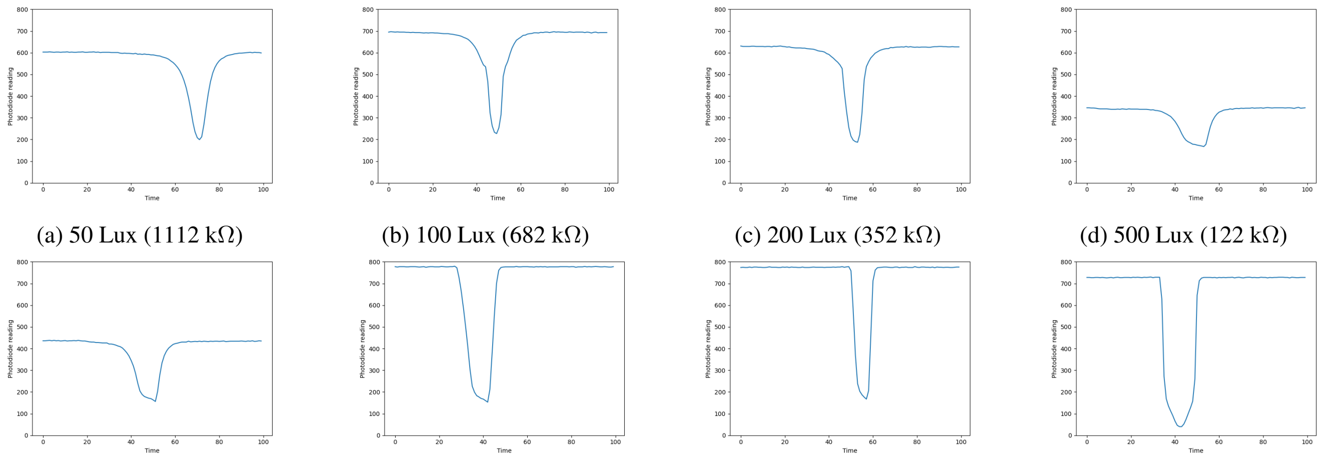
5.2 Impact of photodiode placement

To study the impact of photodiode placement a custom PCB was built. This board, as shown in Figure 1, contains various positions where the OPT101s can be placed, these positions include those described in Table 2. Special IC-sockets were soldered on to the board, which allows for easy reconfiguration of the photodiodes by removing and re-inserting the photodiodes, much like a breadboard. The PBC also offers other advantages over, a breadboard implementation. First of all the fact that components are soldered in place means that no data is inconsistent due to loose wires, and the absence of wires prevents not only ambient lighting from getting blocked but also prevents the hand performing gestures from getting affected by wires.

Each configuration of the photodiodes will be scored based on performance. This is done by first collecting data from hand gestures. Then normalizing the raw data by passing it trough the pre-processing pipeline, developed by another team member in [6]. The final normalized data is then used and, with the help of a dynamic time warping (DTW) algorithm, scored. This DTW algorithm finds the optimal alignment of two gestures, and then calculates the euclidean distance between the two aligned gestures. Each gesture is matched against all other gestures in the dataset of the specific photodiode configuration, including itself. Each

[2] R_{on} is 280Ω at $15V$

[3] $100pA$ leakage current at $18V$ results in $180G\Omega$ for R_{off}



(a) 50 Lux (1112 kΩ) (b) 100 Lux (682 kΩ) (c) 200 Lux (352 kΩ) (d) 500 Lux (122 kΩ)

(e) 2000 Lux (22 kΩ) (f) 5000 Lux (22 kΩ) (g) 11000 Lux (22 kΩ) (h) 150000 Lux (1 kΩ)

Figure 4: Selection of plots showing raw photodiode data. Each measurement is from a "Tap" gesture at varying light intensities (Lux). The system is automatically normalizes the data using resistors, as described in subsection 4.1. All images from 25 Lux to 150000 Lux can be found in Appendix C

match-up will obtain a cost from the dynamic time warping algorithm. A photodiode configuration is scored highly if this cost is high for matches with different gestures, and low for matches with itself. The final result is a similarity matrix for each photodiode placement. This similarity matrix contains the average value calculated by the DTW algorithm, for each combination of gesture match-ups.

6 Results

6.1 Impact of ambient light

Impact of ambient light level

Figure 5 shows the optimal value resistor for each light intensity. It is clear that for every environment there exists a resistor that allows for excellent sensing. From Figure 5 it can be seen that for high light intensities ($>$ 2000 Lux) the resistor required for optimal sensing is very stable. While for low light intensities ($<$ 750 Lux) the resistor required for optimal sensing scales up rapidly.

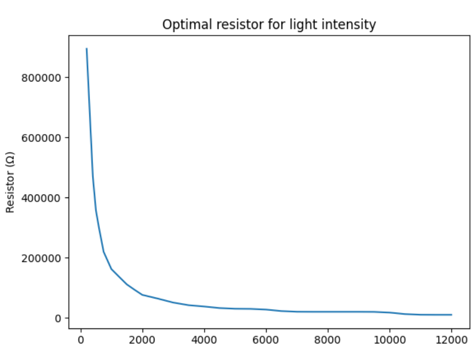
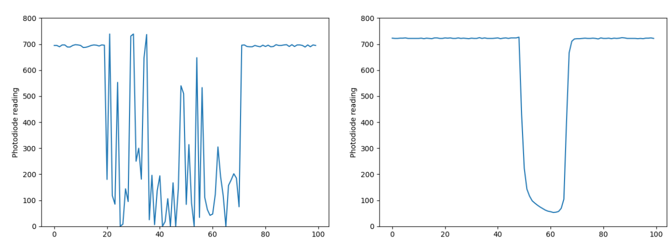


Figure 5: Plot showing optimal resistor values for different light intensities. Light source: the sun

By carefully inspecting Figure 5, it is possible to choose the resistors for the digital potentiometer, described in subsection 5.1. The chosen resistors are $22k\Omega$, $100k\Omega$, $330k\Omega$, and $680k\Omega$. This allows the system access to some low value resistors, while also being able to scale up to $1.132M\Omega$. There is also a $1k\Omega$ resistor in the feedback circuitry which is required for sensing in direct sunlight. This resistor however is not part of the digital potentiometer and can thus not be set or unset; it is always active. In Figure 10 it is shown that by selecting a specific combination of the chosen resistors, the system is able to achieve effective sensing in a range from 50 - 150000 Lux. All plots show that a hand gesture noticeably affects the voltage output of the photodiode, however some plots, specifically Figure 4d, show a more subtle drop in voltage. This is because for 500 Lux the optimal resistor is actually a bit higher than the selected $122k\Omega$ resistor combination. The system only has access to either $122k\Omega$, which is slightly too low or $330k\Omega$, which is too high. Therefore the $122k\Omega$ resistor was chosen as the best alternative for 500 Lux. After data normalization, all signals look the same. Plots from wider range of light intensities along with plots of the normalized signal can be found in Appendix C.

Impact of ambient light type

In direct sunlight the light intensity is often over 100k Lux. In these conditions the photodiode signal is very noisy. This noise can be seen in Figure 6a. While it can be seen that a gesture has occurred, the data is practically unusable. The solution to this problem is an RC low-pass filter consisting of a $1k\Omega$ resistor and a $10\mu F$ capacitor, which achieves a cut-off frequency of approximately $16kHz$. Figure 6b shows the filtered signal. The filtered signal is a substantial improvement over the unfiltered signal, and all noise is removed.



(a) unfiltered (b) filtered

Figure 6: Two plots showing raw photodiode output of a tap gesture performed in direct sunlight (100k Lux, using 1 kΩ). Figure 6a shows the data without an RC low-pass filter, while Figure 6b shows data with an RC low-pass filter.

Hard shadows vs Soft shadows

Gestures made with hard shadows generally perform worse than gestures made with soft shadows. Ambient light types that result in hard shadows, such as direct sunlight or artificial point lights, give rise to difficulties when it comes to sensing gestures that use height as one of their distinctive features. The best example for such a gesture is the double tap gesture. What happens is that the hand covers the photodiodes resulting in a lower voltage output, then the hand goes up. Since there only is a hard shadow no additional light reaches the photodiodes and the voltage output stays low. Finally the hand goes down and finishes the gesture. During the whole gesture the voltage is low, therefore the recognized gesture is not a double tap, but an extended single tap.

Another difference between hard and soft shadows can occur during swipes. If during a swipe there are gaps between the fingers, then there will be sudden spikes in the voltage signal. This happens because the hard shadow gets briefly removed, since light is able to pass trough the gap in the fingers. The overall effect of this is greatly reduced by data normalization, but it can not be removed entirely.

6.2 Impact of photodiode placement

Table 3 shows the average scores of each possible match up between gestures for the 555_606060 photodiode placement. The diagonal elements correspond to match ups between the same gesture, while off-diagonal elements correspond to the scores of match ups of different gestures. The possible photodiode placements should be rewarded for minimizing the scores on the diagonal elements and maximizing the scores on the off-diagonal elements, while they should be penalized for failing to accomplish this. There are two approaches used to propagate this idea to the final results: The first approach is dividing the whole column by the element on the diagonal, shown in Table 4. The second approach is by subtracting the element on the diagonal from the whole column, shown in Table 5. Finally all elements are summed up in order to obtain a single finalized score for each photodiode arrangement. All tables for each photodiode configuration are available in Appendix D.

	left	right	up	down	tap
left	2.08	12.52	8.73	9.39	7.70
right	12.52	2.77	9.52	9.89	8.23
up	8.73	9.52	3.93	11.69	7.42
down	9.39	9.89	11.69	3.80	7.95
tap	7.70	8.23	7.42	7.95	4.48

Table 3: Original scores - 555_606060

	left	right	up	down	tap
left	1.00	4.51	2.22	2.47	1.72
right	6.01	1.00	2.42	2.60	1.84
up	4.19	3.43	1.00	3.08	1.66
down	4.51	3.57	2.97	1.00	1.78
tap	3.70	2.97	1.89	2.09	1.00

Table 4: Column normalized scores - 555_606060

From the results shown in Table 6, it is clear that increasing both the width and the height of the triangle has a positive effect on the overall score of the photodiode configuration. The best performing setup in both described metrics is the equilateral triangle with sides of $6cm$, with the second best having sides of $5cm$.

	left	right	up	down	tap
left	0.00	9.75	4.80	5.59	3.22
right	10.44	0.00	5.59	6.09	3.76
up	6.64	6.75	0.00	7.89	2.94
down	7.31	7.12	7.76	0.00	3.47
tap	5.62	5.46	3.49	4.15	0.00

Table 5: Column subtracted scores - 555_606060

Configuration	Normalized Score	Subtracted Score
666_606060	68.1	150.6
555_606060	64.6	117.8
444_606060	55.5	85.1
333_606060	55.9	62.0
222_606060	44.5	33.2
424_753075	52.2	56.5
626_802080	50.2	79.2
343_4010040	56.3	68.1
464_2513025	61.6	100.1

Table 6: Scores for each photodiode configuration

From this the $6cm$ equilateral triangle looks like the optimal placement, however this placement does come with some issues; the photodiodes are so far apart that sometimes a hand gesture can miss a sensor. This happens most frequently with a tap gesture, where one of the bottom photodiodes is only slightly covered or missed entirely. Figure 7 shows a plot with photodiode data where the photodiode corresponding to the green signal is only slightly covered. The DTW combined with data normalization is able to effectively deal with this error, therefore this does not have any negative effect on the performance scores shown in Table 6. However if the gesture set is extended with for example partial taps, covering only two or a single photodiode then extreme cases of this issue will have a negative effect on the sensing performance.

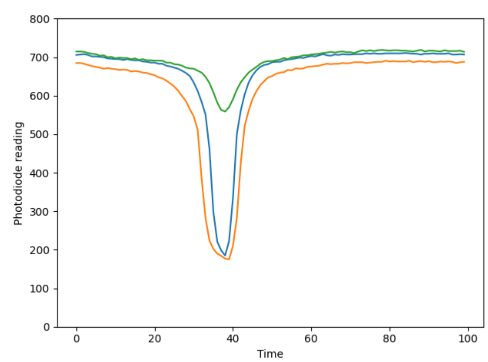


Figure 7: Plot of tap with three photodiodes in an equilateral triangle with sides of $6cm$. The bottom left photodiode (green) is missed by the hand due to a large distance between sensors

The final conclusion, taking into account the performance scores and the fact that large distances may result in missing sensors, is that an equilateral triangle with sides of $5cm$ is the best performing photodiode configuration.

7 Related Work

7.1 VLS Gesture recognition systems

Related work often falls into one of two categories: The system is unable to detect complex gestures, as in SolarGest [12] or the system uses a rather large amount of sensors, as is the case for LightDigit [1] and the system described in the paper by Li et. al. [10]. Each existing system aims to minimize the power required for gesture detection. This is mostly done by using low power microcontrollers and efficient sensors. In [10] and [12] this is taken a step further. These systems use solar cells as both a sensing device as well as an energy harvesting device. This means that the systems require less energy, and might even produce a surplus of energy that can be used for other purposes.

SolarGest was developed to enable gesture detection while minimizing the energy cost. To help in this the chosen sensor was a solar cell, which actively harvests energy. The system was reported to reliably detect up to 6 different gestures: Up, Down, UpDown, DownUp, FlipPalm, and LeftRight. These gestures are extremely basic, with gestures such as Up even being a "sub-gesture" of both UpDown and DownUp. Furthermore the system is not only unable to differentiate LeftRight from RightLeft, it is even unable to differentiate LeftRight from ForwardBack or BackForward. It is obvious that this limitation comes from the fact that only a single sensor is used. With this in mind it is actually impressive that a single sensor can already detect these basic gestures with an accuracy of 96% using basic machine learning. A major shortcoming of this research is that the system was not properly demonstrated in different environments. The report only describes 2 different research environments, where in both cases a light source was purposefully positioned and thus ideal/predictable lighting conditions were utilized during research.

LightDigit is a system that allows a user to write digits, 0 to 9, in the air. To capture these gestures the system employs a 3 x 3 grid of photodiodes. Unfortunately the paper does not describe the systems accuracy or in which environments the system can be deployed.

In [10] two very similar designs are discussed. One design uses 48 photodiodes and is made for use with smart glasses, while the second design uses 44 photodiodes and is compatible with a smart watch. Both designs have joined multiple photodiodes into single sensing units, which results in 16 and 22 sensing units respectively. The implementation for smart glasses is able to detect 5 gestures: left, right, tap, double tap, and double-finger tap. The smart watch implementation also supports the up and down gestures. The accuracy achieved in both systems is very remarkable, all metrics were reported to be higher than 97%. On top of this, the system is also shown to work excellent when deployed in imperfect environments, such as outside and in more darker environments. One aspect where this system lacks is in the practicality of the hardware setup. In the smart watch compatible design the photodiodes are placed in a square around the smart watch itself. Besides this a control pad, a power management board, and a micro controller board are required for the system. All this hardware makes the system heavy, bulky, and impractical to use.

Comparison

Overall the system developed in this paper performs better than the related works. When compared to SolarGest the complexity of the possible gestures is much higher, while using only 2 additional photodiodes. Compared to [10], the gestures are of similar complexity, with the system developed in this paper using significantly less photodiodes. This is possible because this system has had extensive research conducted into photodiode placement, while [10] opted to employ many photodiodes leading to redundancy. The final system discussed was LightDigit. This system looks promising; the gesture complexity is significantly higher, while also using significantly more photodiodes. The major drawback of this report is that no performance scores are mentioned.

Another aspect where most related works are outclassed is in the robustness to the environment. This system is able to perform well in a wide range of light intensities whereas [10] is the only other system capable of achieving this. However this system did also utilize the most photodiodes.

8 Responsible Research

8.1 Ethical implications

The ethical implications of this research are in many areas limited. The only aspect where unfairness to a certain subset of users can occur, is in the photodiode configuration. If the photodiode configuration is too wide, then users with a hand width that is smaller than the distance between the photodiodes might have difficulties in effectively performing gestures that are similar to the tap gesture. In order to minimize this potential ethical unfairness, this issue has been considered during the final decision on the optimal placement of the photodiodes, and it was ultimately decided to use a photodiode configuration that has a slightly worse performance score, but does limit the impact of this issue.

8.2 Reproducibility of results

All results presented in this paper were obtained using ambient light sources that are easily available. Most results used the Sun as ambient light source, with the only exception being the data collected for the photodiode placements at 250 Lux.

Access to code and designs

All code developed for this research along with the code developed by other team members is publicly available on GitHub [4]. The full wiring diagram and PCB design of the circuit is also publicly available on the oshwlab website [5]. Component placement instructions are available in Appendix A, which describes which (value) components correspond to which labels on the PCB.

Availability of components

Reproducibility of results is often difficult. This is especially the case when working with hardware, which may or may not always be accessible or available. In order to maximize the chances that parts are quickly available all components used during this research are labeled as "Active", meaning that production and support for the components will continue for the foreseeable future. In the case that these components are not available then Appendix B details the most important characteristics to consider when selecting alternative components.

9 Conclusions and Future Work

This paper discussed the design of a VLS gesture detection system. Two main aspects of the system have been explored for optimizations. First it was explored how a single OPT101 photodiode could be optimized, then it was explored how the placement of multiple OPT101 photodiodes could be optimized.

Through experimentation it was found which resistors allowed the OPT101 photodiodes to operate within their effective sensing range given an environment with a certain light intensity. To broaden the effective sensing range a custom digital potentiometer was developed, allowing the system access to up to 2^N different combinations of resistors. This paper then demonstrated an implementation with $N = 4$, with resistors of $22k\Omega, 100k\Omega, 330k\Omega$, and $680k\Omega$. It was finally shown that the 16 possible combinations of resistors effectively broadened the effective sensing range; the

[4]https://github.com/StijnW66/CSE3000-Gesture-Recognition

[5]https://oshwlab.com/stijnw66/research-project

system is able to sense in a range from 50 to 150000Lux, and is even able to automatically adapt to a changing environment.

The photodiode configuration was also explored in this paper. For each potential photodiode configuration a small dataset has been created, consisting of various lighting environments. Each configuration was scored by a dynamic time warping algorithm. It was found that larger distances improved the sensing performance of the system, while smaller distances improved the robustness of the system. The best performing configuration was found to be an equilateral triangle with sides of $5cm$.

9.1 Future Work

The developed system is mostly ready for actual deployment inside real-world applications. There are however small adjustments that need to be made and researched for the system to be fully ready. The first adjustment to the system is the addition of a glass or plastic pane that is to be installed in front of the photodiodes. This is necessary to prevent damages to the system and photodiodes, but it needs to be researched how the pane interferes with incoming light and if this affects the overall sensing performance of the system. The second aspect that needs consideration before the system is deployed is the exact environment in which the system will be deployed. The system can theoretically be fine-tuned further by using more/other resistors. This way the system can be optimally created for a specific environment. The final adjustment to the system is that the PCB can be redesigned to use less space and have a lower cost. For this smaller smd components can be used as well as a smaller and cheaper microcontroller.

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A PCB description

The PCB is a $10cm$ x $10cm$ two layer board, consisting of only trough-hole components, and was ordered from JLCPCB. The PCB has 5 main components:

- Feedback Circuit. One for each OPT101 photodiode
- OPT101 triangle. Providing optional placements in order to study the effect. An OPT101 should be placed in one of the bottom left, top, and bottom right positions.
- Arduino Nano 33 BLE
- Low-pass filters. For filtering out high frequency noise (Capacitors not required in most environments, but recommended for improved robustness)
- Indicator LEDs. Indicating which resistors are active. LED on means resistor not in use. (LEDs and 330Ω resistors not required for a functioning system)

Figure 8 depicts a clear image of the blank PCB, with in Table 7 an overview of which components should be placed at each location on the PCB. It is important to note that the micro USB port of the Arduino should face to the right.

Label	Component
R1	$680k\Omega$
R2	$330k\Omega$
R3	$100k\Omega$
R4	$22k\Omega$
R5	$1k\Omega$
R6	$1k\Omega$
C1	$10\mu F$
U1	Arduino Nano 33 BLE
U2	CD4016BE

Table 7: Overview of component placements

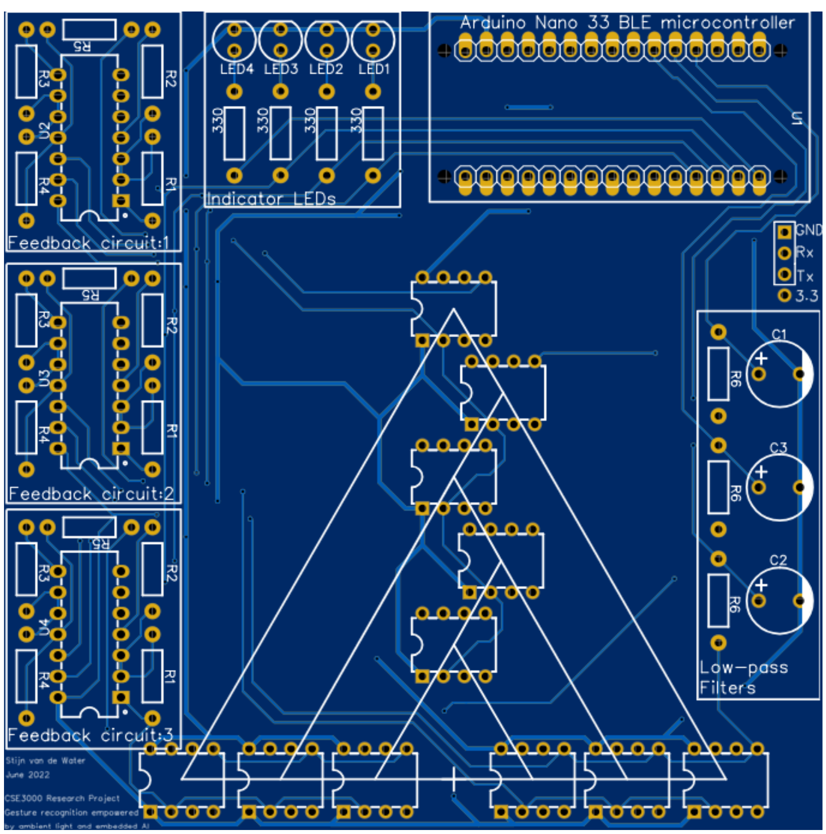


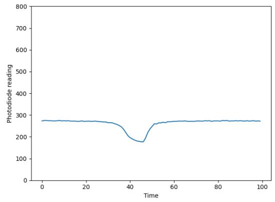
Figure 8: Preview of the PCB (Some naming labels have changed slightly compared to the ordered version)

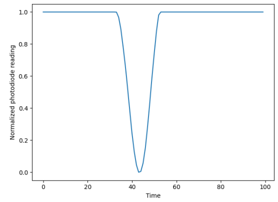
B Component description

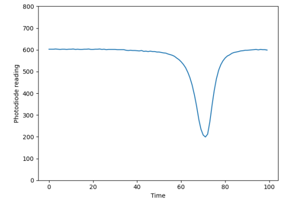
A short description along with important characteristics of each component used in this paper is given. This information can help in selecting suitable alternatives in case any of the components is unavailable.

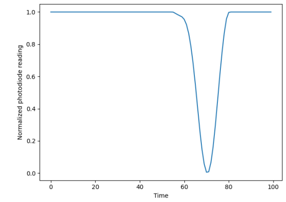
- OPT101 photodiode. The OPT101 is the central component in this research, it is recommended to use this component in order to reproduce the results shown in this paper. In case it is really not possible to use this device it might be possible to construct a custom OPT101 using a photodiode and an operational amplifier.
- CD4016BE. This is a 4 channel SPST switch. Most important characteristics are low ON state resistance ($< 1k\Omega$), high OFF state resistance ($> 1G\Omega$), and good isolation between the control signal and output. It is also preferred for the SPST switch to have a quick ”switching time”, but this is not required (Maybe some modifications delaying the speed of operations are required to the codebase).
- Arduino Nano 33 BLE. This arduino board was selected, as it is a popular and readily available board. An important feature of this board is that it is capable of running Tensorflow Lite for microcontrollers, which is used to perform the gesture classification described in the papers of other team members. In order to reproduce the research presented in this paper a microcontroller should at least have 3 analog pins, 4 digital pins, and preferably at least one serial port for communication with a computer.
- Passive components. The value of all passive components are allowed to be varied to a reasonable extent.

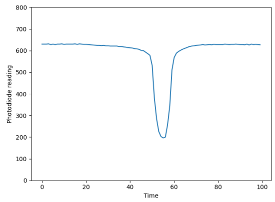
C Additional Figures of original and normalized photodiode output at different light intensities

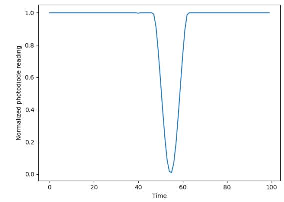

(a) 25 Lux (1132 kΩ) - Original

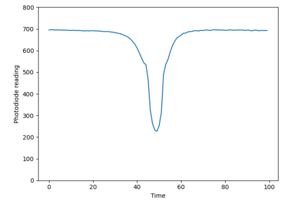

(b) 25 Lux (1132 kΩ) - Normalized

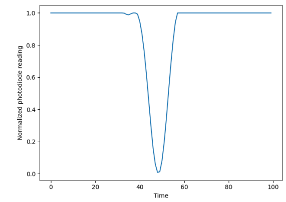

(c) 50 Lux (1132 kΩ) - Original

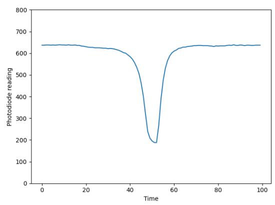

(d) 50 Lux (1132 kΩ) - Normalized

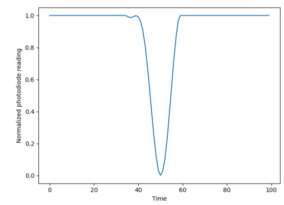

(e) 75 Lux (782 kΩ) - Original

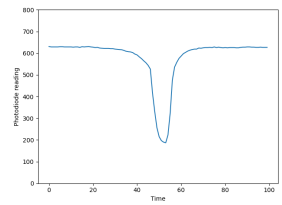

(f) 75 Lux (782 kΩ) - Normalized

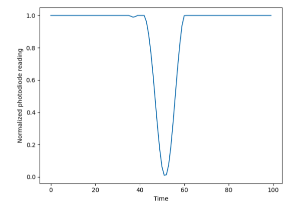

(g) 100 Lux (682 kΩ) - Original

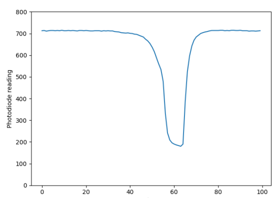

(h) 100 Lux (682 kΩ) - Normalized

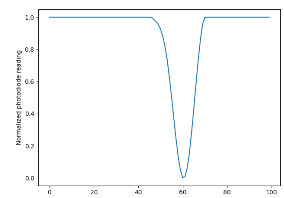

(i) 150 Lux (452 kΩ) - Original

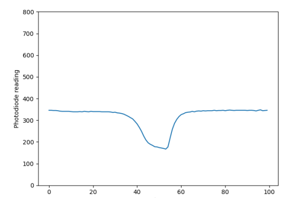

(j) 150 Lux (452 kΩ) - Normalized

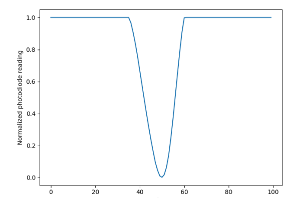

(k) 200 Lux (352 kΩ) - Original

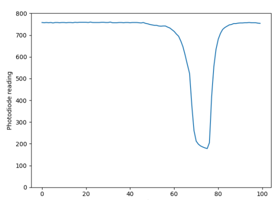

(l) 200 Lux (352 kΩ) - Normalized

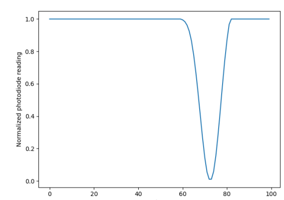

(m) 250 Lux (330 kΩ) - Original

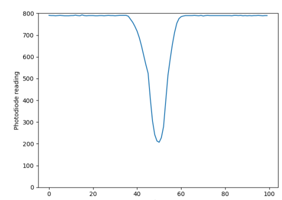

(n) 25- Lux (330 kΩ) - Normalized

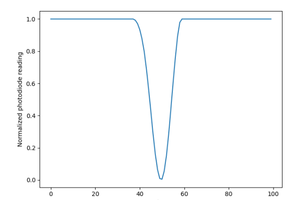

(o) 500 Lux (122 kΩ) - Original

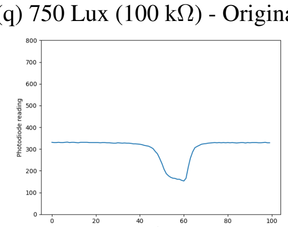

(p) 500 Lux (122 kΩ) - Normalized

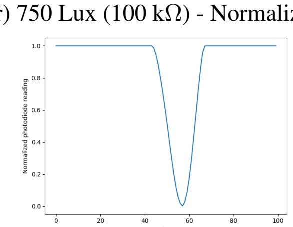

(q) 750 Lux (100 kΩ) - Original

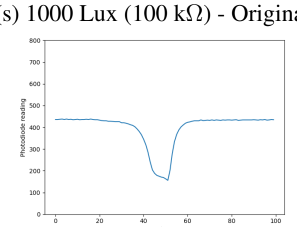

(r) 750 Lux (100 kΩ) - Normalized

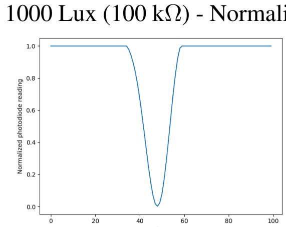

(s) 1000 Lux (100 kΩ) - Original

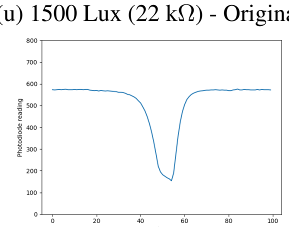

(t) 1000 Lux (100 kΩ) - Normalized

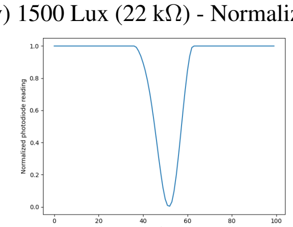

(u) 1500 Lux (22 kΩ) - Original

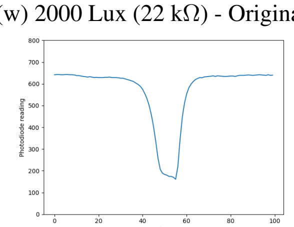

(v) 1500 Lux (22 kΩ) - Normalized

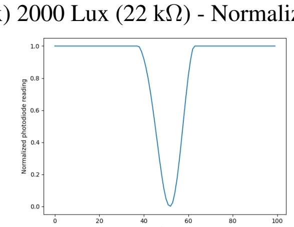

(w) 2000 Lux (22 kΩ) - Original

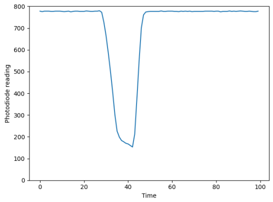

(x) 2000 Lux (22 kΩ) - Normalized


(y) 2500 Lux (22 kΩ) - Original

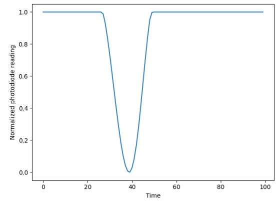

(z) 2500 Lux (22 kΩ) - Normalized


(aa) 3000 Lux (22 kΩ) - Original

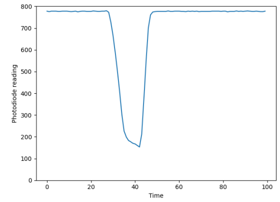

(ab) 3000 Lux (22 kΩ) - Normalized



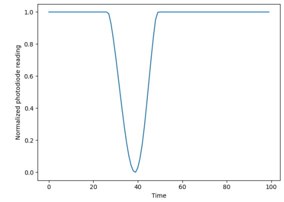
(a) 5000 Lux (22 kΩ) - Original



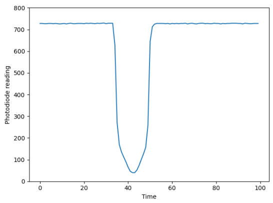
(b) 5000 Lux (22 kΩ) - Normalized



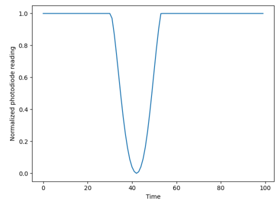
(c) 5000 Lux (22 kΩ) - Original



(d) 5000 Lux (22 kΩ) - Normalized



(e) 15000 Lux (0 kΩ) - Original



(f) 15000 Lux (0 kΩ) - Normalized

Figure 10: All figures from light intensity 25 to 150000 Lux. Both the raw photodiode data and normalized data is presented. All plots are from a tap gesture.

D Additional Tables containing results of DTW for all photodiode configurations.

Configuration: 666_606060

	left	right	up	down	tap
left	2.62	15.42	10.90	11.33	9.11
right	15.42	3.18	11.73	12.21	10.40
up	10.90	11.73	4.51	13.92	8.72
down	11.33	12.21	13.92	4.41	9.40
tap	9.11	10.40	8.72	9.40	4.19

Original

	left	right	up	down	tap
left	1.00	4.84	2.42	2.57	2.18
right	5.88	1.00	2.60	2.77	2.48
up	4.16	3.68	1.00	3.16	2.08
down	4.32	3.83	3.08	1.00	2.24
tap	3.47	3.27	1.93	2.13	1.00

Column normalized

	left	right	up	down	tap
left	0.00	12.23	6.39	6.93	4.92
right	12.79	0.00	7.21	7.80	6.21
up	8.28	8.54	0.00	9.52	4.54
down	8.71	9.02	9.41	0.00	5.21
tap	6.49	7.21	4.21	4.99	0.00

Column subtracted

Configuration: 555_606060

	left	right	up	down	tap
left	2.08	12.52	8.73	9.39	7.70
right	12.52	2.77	9.52	9.89	8.23
up	8.73	9.52	3.93	11.69	7.42
down	9.39	9.89	11.69	3.80	7.95
tap	7.70	8.23	7.42	7.95	4.48

Original

	left	right	up	down	tap
left	1.00	4.51	2.22	2.47	1.72
right	6.01	1.00	2.42	2.60	1.84
up	4.19	3.43	1.00	3.08	1.66
down	4.51	3.57	2.97	1.00	1.78
tap	3.70	2.97	1.89	2.09	1.00

Column normalized

	left	right	up	down	tap
left	0.00	9.75	4.80	5.59	3.22
right	10.44	0.00	5.59	6.09	3.76
up	6.64	6.75	0.00	7.89	2.94
down	7.31	7.12	7.76	0.00	3.47
tap	5.62	5.46	3.49	4.15	0.00

Column subtracted

Configuration: 444_606060

	left	right	up	down	tap
left	2.07	9.63	7.19	8.22	5.89
right	9.63	2.38	7.68	8.32	6.14
up	7.19	7.68	3.86	10.21	6.03
down	8.22	8.32	10.21	5.02	6.36
tap	5.89	6.14	6.03	6.36	3.25

Original

	left	right	up	down	tap
left	1.00	4.05	1.86	1.64	1.82
right	4.66	1.00	1.99	1.66	1.89
up	3.48	3.23	1.00	2.03	1.86
down	3.98	3.50	2.65	1.00	1.96
tap	2.85	2.58	1.56	1.27	1.00

Column normalized

	left	right	up	down	tap
left	0.00	7.25	3.33	3.20	2.65
right	7.56	0.00	3.83	3.30	2.89
up	5.12	5.31	0.00	5.19	2.79
down	6.16	5.94	6.36	0.00	3.12
tap	3.82	3.76	2.18	1.34	0.00

Column subtracted

Configuration: 333_606060

	left	right	up	down	tap
left	1.57	6.90	5.25	5.53	4.48
right	6.90	1.65	5.32	5.26	4.53
up	5.25	5.32	2.70	6.89	4.85
down	5.53	5.26	6.89	2.64	4.66
tap	4.48	4.53	4.85	4.66	2.77

Original

	left	right	up	down	tap
left	1.00	4.18	1.94	2.09	1.62
right	4.39	1.00	1.97	1.99	1.64
up	3.34	3.22	1.00	2.61	1.75
down	3.52	3.19	2.55	1.00	1.68
tap	2.85	2.75	1.80	1.76	1.00

Column normalized

	left	right	up	down	tap
left	0.00	5.24	2.55	2.89	1.71
right	5.33	0.00	2.62	2.62	1.77
up	3.68	3.67	0.00	4.25	2.08
down	3.96	3.61	4.19	0.00	1.90
tap	2.91	2.88	2.15	2.02	0.00

Column subtracted

Configuration: 222_606060

	left	right	up	down	tap
left	1.27	4.45	3.50	3.69	3.05
right	4.45	1.52	3.68	3.90	3.26
up	3.50	3.68	2.54	4.67	3.25
down	3.69	3.90	4.67	2.55	3.26
tap	3.05	3.26	3.25	3.26	2.17

Original

	left	right	up	down	tap
left	1.00	2.92	1.38	1.45	1.40
right	3.49	1.00	1.45	1.53	1.50
up	2.75	2.41	1.00	1.83	1.49
down	2.90	2.56	1.84	1.00	1.50
tap	2.39	2.14	1.28	1.28	1.00

Column normalized

	left	right	up	down	tap
left	0.00	2.93	0.96	1.15	0.88
right	3.18	0.00	1.14	1.35	1.09
up	2.22	2.15	0.00	2.12	1.07
down	2.42	2.37	2.13	0.00	1.09
tap	1.78	1.74	0.70	0.71	0.00

Column subtracted

Configuration: 626_802080

	left	right	up	down	tap
left	2.30	4.87	7.04	8.20	4.57
right	4.87	2.53	7.07	8.38	4.65
up	7.04	7.07	3.37	12.87	7.46
down	8.20	8.38	12.87	5.10	8.25
tap	4.57	4.65	7.46	8.25	3.58

Original

	left	right	up	down	tap
left	1.00	1.93	2.09	1.61	1.28
right	2.12	1.00	2.10	1.64	1.30
up	3.07	2.80	1.00	2.52	2.09
down	3.57	3.32	3.82	1.00	2.31
tap	1.99	1.84	2.21	1.62	1.00

Column normalized

	left	right	up	down	tap
left	0.00	2.35	3.67	3.10	0.99
right	2.58	0.00	3.70	3.27	1.07
up	4.75	4.54	0.00	7.77	3.88
down	5.90	5.85	9.51	0.00	4.67
tap	2.27	2.13	4.09	3.15	0.00

Column subtracted

Configuration: 464_2513025

	left	right	up	down	tap
left	2.23	13.50	9.78	8.42	8.62
right	13.50	2.31	9.04	8.88	8.90
up	9.78	9.04	4.29	6.45	5.63
down	8.42	8.88	6.45	3.71	5.32
tap	8.62	8.90	5.63	5.32	4.71

Original

	left	right	up	down	tap
left	1.00	5.83	2.28	2.27	1.83
right	6.05	1.00	2.11	2.40	1.89
up	4.39	3.91	1.00	1.74	1.20
down	3.78	3.84	1.50	1.00	1.13
tap	3.87	3.84	1.31	1.44	1.00

Column normalized

	left	right	up	down	tap
left	0.00	11.18	5.49	4.72	3.91
right	11.27	0.00	4.75	5.18	4.19
up	7.55	6.72	0.00	2.74	0.92
down	6.19	6.57	2.16	0.00	0.61
tap	6.39	6.58	1.34	1.61	0.00

Column subtracted

Configuration: 424_753075

	left	right	up	down	tap
left	1.72	4.49	4.71	5.11	3.34
right	4.49	1.84	4.73	5.34	3.50
up	4.71	4.73	2.45	8.07	4.92
down	5.11	5.34	8.07	2.20	5.09
tap	3.34	3.50	4.92	5.09	2.33

Original

	left	right	up	down	tap
left	1.00	2.44	1.92	2.33	1.44
right	2.61	1.00	1.93	2.43	1.50
up	2.74	2.58	1.00	3.67	2.11
down	2.97	2.90	3.29	1.00	2.19
tap	1.95	1.90	2.01	2.31	1.00

Column normalized

	left	right	up	down	tap
left	0.00	2.65	2.26	2.91	1.02
right	2.77	0.00	2.28	3.14	1.17
up	3.00	2.90	0.00	5.87	2.59
down	3.39	3.50	5.62	0.00	2.76
tap	1.63	1.66	2.47	2.89	0.00

Column subtracted

Configuration: 343_4010040

	left	right	up	down	tap
left	1.68	9.55	6.26	5.72	5.41
right	9.55	2.01	6.26	6.83	5.67
up	6.26	6.26	3.23	5.56	4.07
down	5.72	6.83	5.56	3.01	4.03
tap	5.41	5.67	4.07	4.03	2.73

Original

	left	right	up	down	tap
left	1.00	4.75	1.94	1.90	1.98
right	5.68	1.00	1.94	2.27	2.08
up	3.72	3.11	1.00	1.85	1.49
down	3.40	3.40	1.72	1.00	1.48
tap	3.21	2.82	1.26	1.34	1.00

Column normalized

	left	right	up	down	tap
left	0.00	7.54	3.03	2.71	2.68
right	7.87	0.00	3.03	3.82	2.94
up	4.58	4.25	0.00	2.55	1.34
down	4.04	4.82	2.33	0.00	1.30
tap	3.73	3.66	0.84	1.02	0.00

Column subtracted